Analysis of advanced European nuclear fuel cycle scenarios including transmutation and economic estimates

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A B S T R A C T

Four European fuel cycle scenarios involving transmutation options (in coherence with PATEROS and CP-ESFR EU projects) have been addressed from a point of view of resources utilization and economic estimates. Scenarios include: (i) the current fleet using Light Water Reactor (LWR) technology and open fuel cycle, (ii) full replacement of the initial fleet with Fast Reactors (FR) burning U–Pu MOX fuel, (iii) closed fuel cycle with Minor Actinide (MA) transmutation in a fraction of the FR fleet, and (iv) closed fuel cycle with MA transmutation in dedicated Accelerator Driven Systems (ADS). All scenarios consider an intermediate period of GEN-III+ LWR deployment and they extend for 200 years, looking for long term equilibrium mass flow achievement.

The simulations were made using the TR_EVOL code, capable to assess the management of the nuclear mass streams in the scenario as well as economics for the estimation of the levelized cost of electricity (LCOE) and other costs.

Results reveal that all scenarios are feasible according to nuclear resources demand (natural and depleted U, and Pu). Additionally, we have found as expected that the FR scenario reduces considerably the Pu inventory in repositories compared to the reference scenario. The elimination of the LWR MA legacy requires a maximum of 55% fraction (i.e., a peak value of 44 FR units) of the FR fleet dedicated to transmutation (MA in MOX fuel, homogeneous transmutation) or an average of 28 units of ADS plants (i.e., a peak value of 51 ADS units).

Regarding the economic analysis, the main usefulness of the provided economic results is for relative comparison of scenarios and breakdown of LCOE contributors rather than provision of absolute values, as technological readiness levels are low for most of the advanced fuel cycle stages. The obtained estimations show an increase of LCOE – averaged over the whole period – with respect to the reference open cycle scenario of 20% for Pu management scenario and around 35% for both transmutation scenarios. The main contribution to LCOE is the capital costs of new facilities, quantified between 60% and 69% depending on the scenario. An uncertainty analysis is provided around assumed low and high values of processes and technologies.

1. Introduction

The efficient design of strategies for the long-term sustainability of nuclear energy requires the study of transition scenarios from the current fuel cycle to a future one with advanced technology and concepts. This kind of studies provides answers to different aspects of transition scenarios, such as the period of time needed to reach equilibrium, the number and date of introduction of facilities in the fuel cycle, the amount of stored material, and the nuclear waste. Moreover, these studies can be improved with economics analyses, also required to evaluate the viability of a fuel cycle strategy.

In this work the transition from the existing LWR fleet to strategies with advanced reactors is analyzed, including Generation III+ reactors in a European framework, involving a number of European Union countries according to the choice performed in PATEROS (González-Romero et al., 2007). The analysis of these fuel cycle scenarios has been performed following the recommendations specified in reference documents provided by the CP-ESFR EU project (Bianchi et al., 2009) and ARCAS EU project (Klaasen et al., 2012).

These nuclear fuel cycle scenarios have been evaluated using TR_EVOL (Álvarez-Velarde et al., 2010), a module developed by CIEMAT to improve the capabilities of its burn-up simulation system,

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EVOLCODE 2.0 (Álvarez-Velarde et al., 2007). TR_EVOL has been designed to study different short-, medium- and long-term options for the introduction of various types of nuclear reactors and for the usage of associated nuclear material, giving due consideration to the isotopic composition of the material in any stage of the fuel cycle: essentially uranium, plutonium, minor actinides and fission products. Moreover, the application of its economic module can give additional and relevant information to study the fuel cycle in a global context.

2. Objectives

The main goal of this work is to analyze – in economic and resources terms – the impact of the implementation of different representative scenarios for a European nuclear fleet with a constant demand of energy. This objective requires the estimation of:

- Natural uranium and plutonium needs.
- Quantity of fast reactors (FR) and accelerator-driven subcritical systems (ADS) facilities to reach the equilibrium of minor actinides (MA) content in the fleet.
- The MA evolution for transmutation scenarios.
- The Levelized Cost of Electricity (LCOE) for each scenario and by reactor type.
- Impact in the LCOE of its main components.

3. Main hypotheses and input data

3.1. Hypotheses for the fuel cycle processes

The scenarios assessed here are formed by five reactor types that are named depending on the technology and the fuel type used:

- *LWR_UOX*: For light water reactors (LWR Gen II, pressurized water reactor – PWR – or boiling water reactor – BWR-type) with UO_2 fuel.
- *LWR_MOX*: For LWR (Gen II, PWR or BWR) with MOX fuel.
- *LWR_GENIII*: For LWR (Gen III+) with 100% of UO_2.
- *SFR (T-SFR)*: For sodium-cooled FR with MOX fuel (with transmutation capability for 2.5% of MA homogeneously distributed in the fuel). The average amount of Pu in the MOX fuel is close to 15%, but it depends on the isotopic composition of the fabrication streams.
- *ADS*: For ADS with inert matrix fuel (45% Pu and 55% MA).

The simulation characteristics of the reactors are summarized in Table 1 and have been obtained from Refs. (Bianchi et al., 2009; Klaasen et al., 2012).

Note that in this table, the ADS Pu conversion ratio accounts for Pu occurrence after Am capture and Cm decay.

The composition of the initial legacy of spent fuel (SF) in the fleet comes from 7 EU nuclear countries, assumed associated for back-end fuel management purposes. The accumulated actinide mass until year 2010 is provided from EU CP-ESFR project, as well as from the previous PATEROS project (González-Romero et al., 2007). This document estimates that the total amount of plutonium in year 2010 is 386.6 t. In addition, 126.7 t are released from one country in year 2022 (phase out assumption in that country) and added to the initial legacy.

Table 1
General parameters for each reactor type.

	LWR_UOX	LWR_MOX	LWR_GENIII	SFR	ADS
Plant thermal power (MWth)	2965	2965	4400	3600	400
Plant thermal efficiency (%)	34	34	34	40	32
Plant electrical power (MWe)	1008	1008	1496	1440	128
Plan capacity factor (%)	80	80	85	80	75
Fuel burn-up (GWd/tHM)	50	45	55	99	150
Lifetime (yr)	40	40	60	60	60
Conversion ratio (Pu)	0.42	0.66	0.48	1.08	1.00

Regarding the UO_2 fuel enrichment, no maximum limit in the SWUs plants capacity has been considered here. The tails assay for ^{235}U enrichment is 0.25% until 2020 and 0.20% after this year. Moreover, the time required for fuel fabrication is 1 year for any type of fuel. No restriction in fabrication capacity has been considered in this work.

Three reprocessing plants are considered in these scenarios depending on the fuel types (LWR fuel, SFR fuel and ADS fuel). The minimum cooling time for the irradiated fuels before reprocessing is 5 years. Reprocessing period lasts 1 year. A reprocessing loss rate for Pu, U and MA of 0.1 (wt%) has been considered. For the fabrication stage, no loss rate has been taken into account in this exercise, in coherence with CP-ESFR reference scenario.

According to NEA/OECD (2010) the total amount of uranium at world level rises to 16.8 million t, ignoring the uranium resources in phosphates and seawater. Although this value is not directly used in this work, it is a reference to be respected at world scale.

3.2. Hypotheses for the fuel cycle costs

The LCOE can be defined as a sum of four components, averaged in a period of time:

- *Investment cost*: It includes the overnight cost and financial costs (financial costs are additionally split in interest during construction, where a large disbursement takes place, and interest for the financing).
- *Fuel cost*: In this study, this contribution represents the front-end cost, including structural fuel assembly and required reprocessing in case of MOX and advanced fuel fabrication.
- *Operation and Maintenance (O&M)*: Annual cost for the plant, which depends on the installed capacity.
- *Decommissioning, Dismantling and waste Disposal (DDD)*: In addition to reactor plant dismantling, the fuel waste final management associated to the back-end fuel costs is included here; i.e., repository costs.

All costs, excluding those ones for DDD, are summarized in Table 2 where the Best Case (BC) unit costs for each item, taken from the ARCAS project, are shown. Plant and reprocessing technologies have different readiness levels; therefore a cost uncertainty band with low and upper values is provided around the Best Case values. Uncertainties are taken from bibliography NEA/OECD (2006), and they were duly adjusted regarding inflation and currency conversion.

Concerning MOX and advanced fuel costs, there are two contributions: (i) the assembly costs (simply named 'fabrication' in the table) and (ii) a mixed reprocessed material compound cost in terms of new fabricated fuel. This compound price is obtained after assumptions of fixed unitary cost of spent fuel reprocessing, which implicitly include the investment, O&M and decommissioning costs of fabrication and reprocessing facilities. In Table 2 assembly, unitary reprocessing and compound costs are shown but not the total final cost (i.e., addition of assembly and compound fabricated fuel costs).

Current LWR_UOX and LWR_MOX plants are working since the 1970s and 1980s, while our analysis starts in year 2010. Hence, we assumed them to be paid off at the beginning of the scenarios and therefore it is considered that generation costs for this type of plants will only include fuel, O&M and DDD costs, excluding all their investment cost.

For the DDD cost, an average value of 15% of the reactor overnight cost has been applied as Decommissioning and Dismantling

Table 2
Cost information per reactor type.

Reactor technology	LWR-UOX			LWR-MOX			LWR-GENIII		
	Lower bound	Best Case	Upper bound	Lower bound	Best Case	Upper bound	Lower bound	Best Case	Upper Bound
Investment costs									
Overnight (€/kWhe)	1875	2500	2970	1875	2500	2970	2251	3002	3565
Interest (financial) (%)	8	8	8	8	8	8	8	8	8
Constr. Time (yr)	4	6	8	4	6	8	4	6	8
Interest (construction) (%)	8	8	8	8	8	8	8	8	8
O&M costs									
M€/GWe/yr	56	75	94	56	75	94	56	75	94
Fuel costs									
Natural U €/kgU3O8	40	100	160	–	–	–	40	100	160
Conversion 1 (€/kgU)	5	8	13	–	–	–	5	8	13
Enrichment (€/SWU)	80	100	120	–	–	–	80	100	120
Conversion 2 (€/kgU)	5	8	13	–	–	–	5	8	13
Fabrication cost, assembly contribution (€/kg-fabricated fuel)	200	250	300	800	1000	1200	200	250	300
Unitary reprocessing cost (€/kg-spent fuel)	875	1000	1125	875	1000	1250	875	1000	1125
Compound cost of fuel, mixed reprocessing contribution (€/kg-fabricated fuel)	–	–	–	5400	6100	6900	–	–	–
	SFR			T-SFR			ADS		
Investment costs									
Facility (€/kWhe)	2465	3902	4724	2465	3902	4724	11,500	14,760	18,000
Interest (Financial) (%)	8	8	8	8	8	8	8	8	8
Constr. time (yr)	4	6	8	4	6	8	4	6	8
Interest (construction) (%)	8	8	8	8	8	8	8	8	8
O&M costs									
M€/GWe/yr	65	86	108	65	86	108	168	223	279
Fuel costs									
Fabrication cost, assembly contribution (€/kg-fabricated fuel)	1000	1500	2000	5000	10,000	15,000	9100	20,000	27,300
Unitary reprocessing cost (€/kg-spent fuel)	455	1000	1364	4550	10,000	13,640	14,300	20,000	34,300
Compound cost of fuel, mixed reprocessing contribution (€/kg-fabricated fuel)[a]	1400	2000	2400	4000	8300	11,200	10,800	15,700	28,100

[a] This line in the table accounts for the cost contribution of different reprocessed materials, available from different technologies as scenarios develop. Values are obtained after application of reprocessing unitary input costs per technology and they are dependent of strategies assumed for combination of available masses. For instance, some 3 kg of LWR-MOX of spent fuel (SF) are necessary to reprocess at beginning of Scenario 2 to obtain 1 kg of SFR fabricated fuel (FF), which means (3 kg-SF/1 kg-FF) $*$ 1000 €/kg-SF = 3000 €/kg-FF. As the scenario proceeds a new source appears from SFR spent fuel. Therefore, as SFR BR $\sim$ 1, at advanced scenario stages we have (1 kg-SF/1 kg-FF) $*$ 1000 €/kg-SF = 1000 €/kg-FF. Note that value shown in the table 2 is an average over the whole scenario period (2000 €/kg-FF, in this case), which in addition it has been rounded off to be used as input for the economic module.

cost. Concerning disposal, Interim Disposal (ID) and Final Disposal (FD) costs are taken into account. They are estimated following the TR_EVOL model consisting in dividing their cost into a fixed cost plus and a variable cost. For the ID, the variable cost depends mainly on the mass to store. For the FD, the variable cost represents the galleries length cost in an underground geological repository. Both variable costs include canisters fabrication and operation.

Concerning FD storage, the main approach is to be limited by thermal and mass constraints in the packages to be placed in the repository. As an example, in REDIMPACT project (RED IMPACT, 2008) it was assumed 4 LWR–UOX spent fuel assemblies per package, and 1 LWR–MOX spent fuel per package. In case of HLW obtained in advanced closed cycles, standard vitrified packages are considered to be obtained, then assuming a certain quantification of actinide and FP masses based in same Ref. RED-IMPACT (2008). These amounts have been directly correlated to final gallery dimensions in this study.

4. Scenario description

Scenarios start at year 2010 with 91.2 GWe generated (112.9 GWe installed) by the seven EU associated countries, with LWR_UOX and LWR_MOX reactors, both of them Gen II technology, and they finish in year 2210 with the same value of total generated power. Four fuel cycle scenarios are analyzed. All of them consider an initial period of LWR Gen II decommissioning since year 2020 to 2025 for LWR_MOX and from 2020 to 2050 for LWR_UOX.

- *Scenario 1 or reference (open cycle) scenario (SCN-1)*: At the assumed end of life of the LWR plants, they are replaced by a LWR_GENIII fleet that last until the end of the analysis period 2210.
- *Scenario 2 (SCN-2)*: The electricity generation of the LWR plants is replaced by LWR_GENIII since year 2021 and SFR since year 2040 until 2/3 and 1/3 of the energy are reached respectively at year 2050, and 100% of the electricity generated by SFR, meaning around 79 reactors, at end of the century.
- *Scenario 3 (SCN-3)*: Similar to Scenario 2, the only difference is that 56% of the SFR plants commissioned are loaded with MA fuel for net transmutation (since here T-SFR), meaning around 44 reactors at the end of cycle. The rest 44% (or 35 reactors) of SFR burn only Pu.
- *Scenario 4 (SCN-4)*: In this scenario, transmutation of MA is made by ADS, while SFR do not load fuel with MA content. Concerning LWR, this scenario has no changes regarding SCN-2. The amount of electricity generated by the ADS – replacing some SFR – depends on its transmutation potential and the Pu and MA availability. A maximum amount of 51 ADS and 37 units is reached at the end of cycle giving an average of electric contribution of 3% along the cycle.

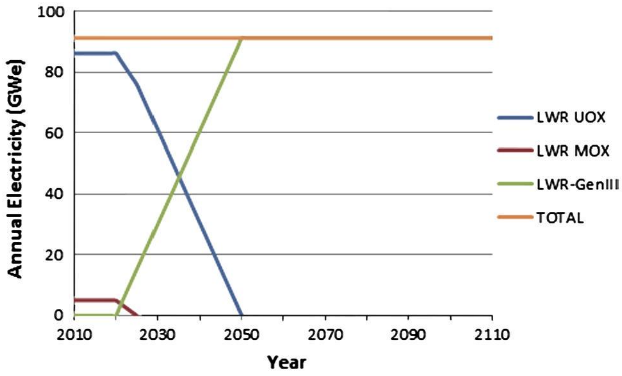

Fig. 1. SCN-1 power generation (open cycle).

Figs. 1–4 show the contribution to the energy per reactor type in GWe. Beyond year 2110, installed capacity of the scenario remains unchanged until 2210 except in SCN-4 which undergoes small changes due to variations in the number of ADS to reach the MA equilibrium mass. Each reactor is ensured to last for 60 years.

5. Simulation tool: TR_EVOL module description

The TR_EVOL module (Álvarez-Velarde et al., 2010) has been designed to evaluate different options for the fuel cycle scenario, enhancing the capabilities of the burn-up simulation system EVOLCODE (Álvarez-Velarde et al., 2007). In particular, diverse nuclear power plants (PWR, SFR, ADS, etc.), having possibly different types of fuels (UO2, MOX, etc.), and the associated fuel cycle facilities (enrichment, fuel fabrication, reprocessing, interim storage, waste storage, geological disposal) can be assessed. The module is intended to simulate each reactor fleet as a single averaged macro-reactor, although it can also simulate individually each reactor of the fleet if required (requiring however large computer resources). Due to this purpose and assuming that the nuclear fleet is large enough (usually tens of reactors), every magnitude is provided per year. Hence, large fluctuations of operational parameters on individual cycle facilities are averaged over the year.

Each fuel cycle storage facility is represented in TR_EVOL by one or several different buffers. For instance, a nuclear fleet might consist of a series of PWR with N different ^{235}U enrichments fuels. Hence, data concerning fresh fuels with different enrichments would be stored in N different buffers containing the isotopic vector and the total amount of material present in that storage. Storage facilities taken into account in a general fuel cycle (other could be included when necessary for particular cycles) are fresh fuel for

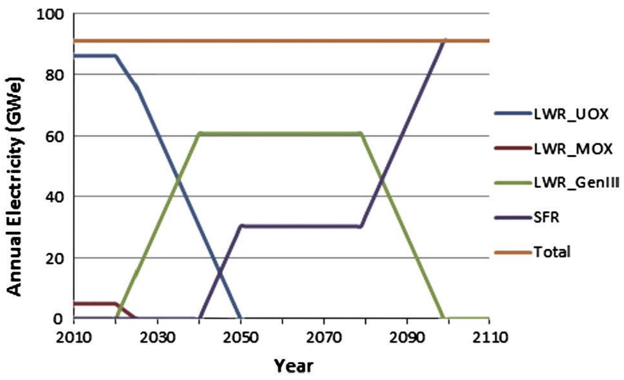

Fig. 2. SCN-2 power generation.

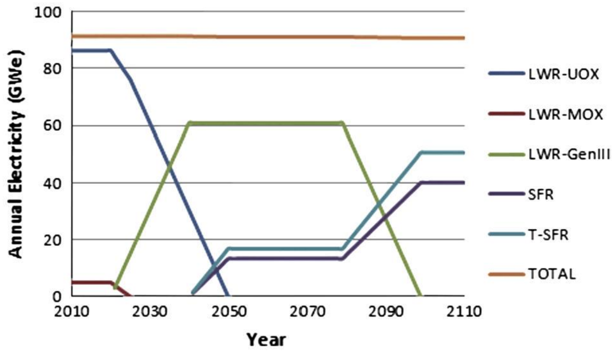

Fig. 3. SCN-3 power generation.

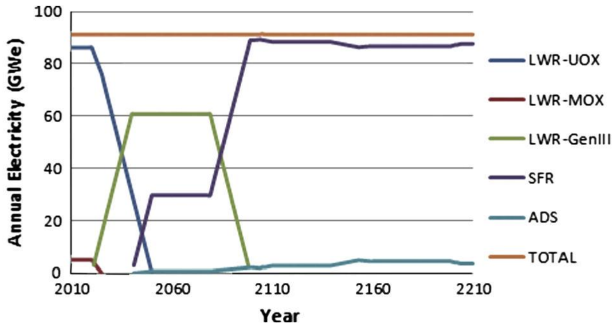

Fig. 4. SCN-4 power generation.

nuclear reactors, SF in cooling storage, separated material from reprocessing and nuclear waste.

Connections between buffers represent mass flows. They can link one buffer to another, but can also join more than two buffers or divide different buffers. The parameters of the cycle facilities and the time-dependent interconnections are described in TR_EVOL using a series of basic operational instructions or rules. Each rule specifies a particular action that is applicable to a particular buffer (decay of stored material) or to a particular interconnection (fuel irradiation, fuel fabrication, reprocessing, etc.). The period of time for which that particular action is active is also specified (for instance, advanced reprocessing may be only applicable from a certain year on).

The evolution of fuel isotopic composition and nuclear materials during the lifetime of the nuclear fleet is performed in TR_EVOL by means of ORIGEN 2.2 (Isotope Generation and Depletion Code) (Croff, 1980) specifically in the decay and irradiation processes. In case of irradiation, the ORIGEN reference cross section libraries or libraries specifically calculated with EVOLCODE 2.0 can be used. In this work, EVOLCODE-made libraries were used for all the fast neutron systems while ORIGEN reference libraries were used for thermal reactors.

The TR_EVOL module for economic assessments provides the Levelized Cost of Electricity making use of the TR_EVOL mass balance output and four main sources of economic information: Investment cost, Fuel cost, Operation and Maintenance (O&M) cost and Waste Management cost. Investment costs take into account the overnight cost of the plant, interest rates, payback periods and construction periods. Fuel cost is calculated using parameters such as raw materials, enrichment, conversions and fabrication in case of UO_2 fuel, or a fixed cost by kg in case of MOX fuel for LWR, FR or ADS. O&M can be explained as a cost by GWe installed. Waste Management cost is the sum of interim and final disposal cost, including fixed and variable costs like shaft, galleries, canisters and glasses (which are limited by heat production), and the decommissioning cost as a percentage of the overnight cost.

Although the TR_EVOL economic module usually provides the LCOE as a best estimate value, the LCOE uncertainties can be additionally assessed via probabilistic distributions for the unit costs. The best estimate case can be executed many times; for each run or history, a simultaneous random sampling of the probability density functions of the unit costs (described as uniform or triangular distributions) has to be carried out to obtain the results. Finally, a statistical analysis of the outputs provides the assessments of the LCOE uncertainties.

To improve the methodology, the possibility of setting correlations between unit costs has been implemented in the code for those costs that are strongly dependent between them. For instance, the overnight cost for LWR_UO_2 and LWR_MOX, or the cost of natural uranium for different LWR, can be considered correlated, meaning that the same random number is used for each of them in the same history. No partial correlations have been implemented in this work, the unit cost can be correlated at 100% or 0%.

6. Main results

6.1. Fuel cycle scenarios analysis

Concerning the resources availability, Fig. 5 shows the natural uranium (NatU) needs for all scenarios. The reference scenario (SCN-1) requires ~3.3 million of tU at the end of the scenario. Considering that the current global energy demand is approximately four times larger than the scenarios energy demand, and that the total amount of uranium at world level at a reasonable prize is five times the U requirements, these U requirements do not seem to be a significant constraint. Advanced scenarios require less than one third of the uranium needed in the reference cycle at the end of the scenario. The NatU curves for these scenarios have two changes in the slope, the first one at year ~2040 when the LWR_GENIII commissioning is completed demanding less NatU, and the second one at year ~2100 when they finish their operation and the scenarios continue just with SFR or ADS fuel.

Regarding Pu availability, i.e. Pu separated or in SF ready for reprocessing, Fig. 6 shows that every advanced scenario has the same tendency, due to the SFR (or T-SFR and ADS) Pu consumption. A first peak of ~1000 t at year 2038 is formed when the first stage of advanced reactors commissioning begins for 10 years, demanding Pu for the fabrication of the MOX new cores. After this period, Pu is accumulated due to the Pu generation in LWR_GENIII and the SFR breeding. The beginning of the second stage of 20 years of advanced reactors commissioning is marked by the second peak of ~1100 t around year 2077 reducing the Pu availability for a period of 20 years. The Pu availability reduction continues for 10 more

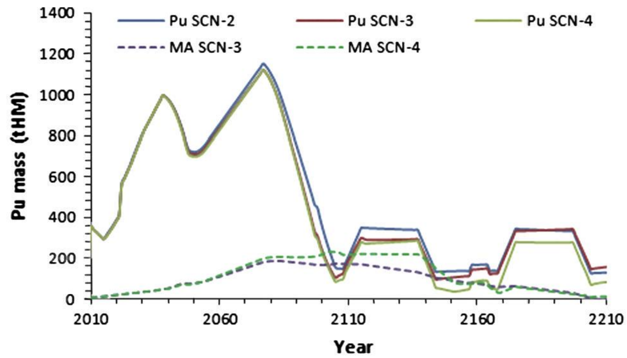

Fig. 6. Availability of Pu and MA separated or ready for reprocessing.

years, caused by the replacement of the advanced reactors from the first stage commissioning. It has to be taken into account that the reactor decommissioning along the cycle leads to unloading significant mass as spent cores; they are also considered in the Pu availability curve.

Additionally, Fig. 6 shows that it is not necessary to operate with high breeding ratios beyond year 2110 since equilibrium can be achieved with a smaller breeding ratio. So, breeding ratios around 1.01–1.03 (Fig. 7) were utilized to keep a reasonable Pu stock to maintain the cycle, avoiding separated Pu in storage with no use.

In scenarios SCN-2, SCN-3 and SCN-4, depleted uranium (DepU) is used for FR fuel fabrication. Fig. 8 shows that DepU for SFR fuel fabrication is not a constraint in the scenarios of this work, as there is enough mass to fabricate fuels for around a thousand of years. Additionally, Fig. 9 shows the evolution of the RepU stock by scenario. Although this material can be also be used for the FR fuel or for its reenrichment in UO2 fuel fabrication EPRI (2010), these options have not been taken into account in this work because their use lead to other implications (generation of different waste streams, for instance) that are beyond this analysis.

Regarding the transmutation performance the figure shows larger amounts of transmuted mass than in the estimations at equilibrium. ARCAS project estimates a transmuted mass of ~6.03 kg/TWhe for the T-SFR stimulated in SCN-3, and 112.5 kg/TWhe for the ADS in SCN-4. However, these estimations have been calculated in equilibrium stages and they do not consider the isotopic evolution of their Pu or MA pool streams for fuel fabrication. Considering this fact, the transmuted mass amount experiences continuous changes along the cycle giving averaged values of 8.2 kg/TWhe for T-SFR and 131 kg/TWhe for ADS. Table 3 shows the Pu and MA inventories stored in the interim and final disposal at year 2210 for the different scenarios. This table shows that scenarios involving

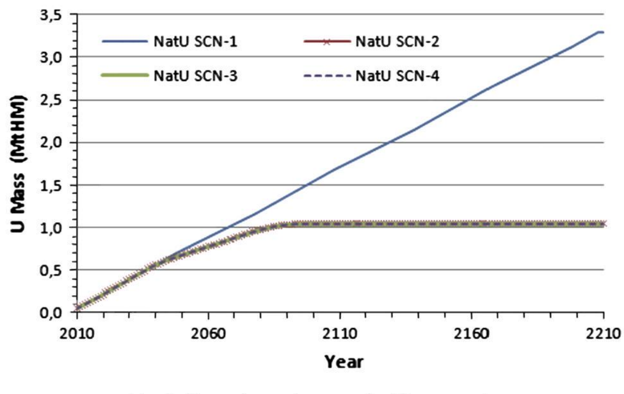

Fig. 5. Natural uranium required by scenario.

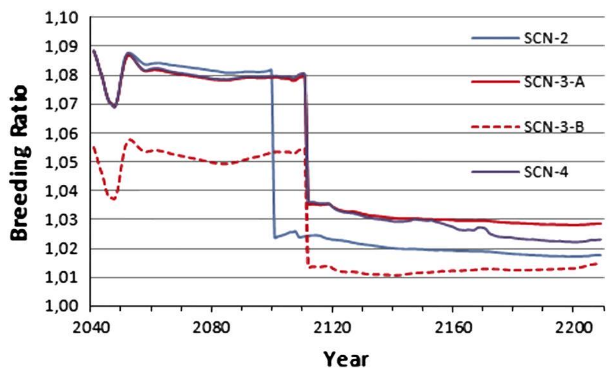

Fig. 7. Breeding Ratio for SFR by scenario. SCN-3-A and SCN-3-B represent the SFR and T-SFR breeding ratios respectively.

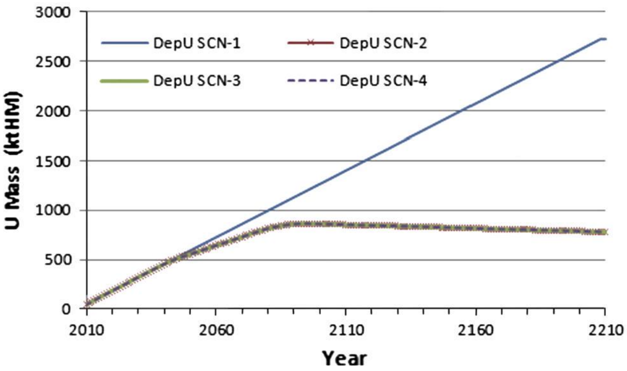

Fig. 8. Depleted uranium needs by scenario.

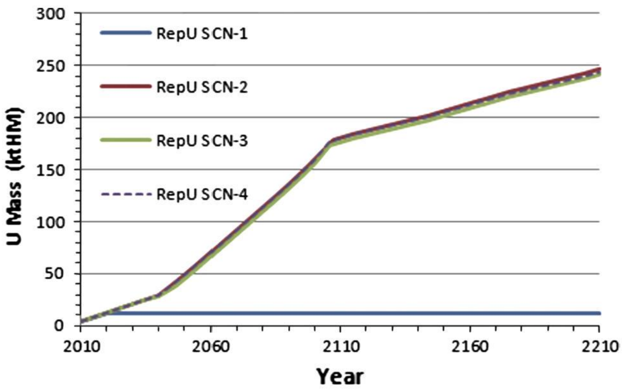

Fig. 9. Reprocessed uranium stock by scenario.

fast reactors reduce significantly the Pu inventory to dispose of, although the MA inventory is not considerably modified unless scenarios with dedicated MA transmutation are performed. In these cases, a reduction factor of ~500 in the MA inventory can be achieved.

The number of reactors dedicated to transmutation at the end of the scenarios is 44 T-SFR units for SCN-3 (out of 79 SFR in total) and 37 ADS for SCN-4. These units numbers have been chosen to reasonably fulfill the hypothesis of having an equilibrium between the amount of MA transmuted and generated at the end of the scenario. In order to reach this equilibrium in SCN-4, a larger number of transmuters is needed in an intermediate period. An arbitrary number of 51 ADS units has been chosen.

Finally, Table 4 shows the High Level Waste (HLW) inventories (including reprocessing losses, non-reprocessed actinides and fission products, and SF assemblies for SCN-1), stored in interim or final disposal for each scenario at year 2210.

6.2. Economics analysis

6.2.1. Best Case cost

Concerning the costs of electricity generation, the LCOE was obtained applying the Base Case (BC) unit costs shown in Table 2.

Table 3
Pu and MA inventories in the interim and final disposal at year 2210 for the different fuel cycle scenarios (t).

	SCN-1	SCN-2	SCN-3	SCN-4
Pu	4697	50.68	20.86	21.79
MA	1134	985.5	2.25	2.03

Table 4
HLW inventories at the end of the scenario in interim and final disposal (t).

	LWR-UOX SFA	LWR-MOX SFA	Rep. UOX	Rep. MOX	Rep. SFR	Rep. ADS
SCN-1	397,296	4280	69.6	0	0	0
SCN-2	0	0	6721	320	9116	0
SCN-3	0	0	6183	277	9232	0
SCN-4	0	0	6183	277	9008	410

Results are shown in Table 5, where the contribution per component or sub-cost (Investment, Fuel, O&M and DDD) to the total is also shown. It can be found that all scenarios have a large dependence on the investment cost, responsible of 60–69% of the energy cost. Results show that the investment cost is explained as financing the overnight cost in ~79% and interest during construction ~21%; a really important contribution.

It should be added that the LCOE is an integral parameter calculated for the whole scenario length (duly averaged by technology and energy share) and every scenario considers an initial period where the investment costs of LWR_UOX and LWR_MOX are not considered, as explained above. Thus, the LCOE should not be considered as an absolute value but a relative one between fuel cycle scenarios with different technologies.

Regarding other costs also calculated in detail, the HLW storage costs are shown in Fig. 10, including the costs of the ID and the FD per scenario for the HLW inventory displayed in Table 4. According to current policies in a number of countries, the HLW mass (formed by fission products, non-recovered actinides and reprocessing losses, or SF in case of SCN-1) has been supposed to be stored temporarily in interim facilities and finally disposed of in a deep repository or final disposal. As shown in the figure there is a notorious difference between the Once-Through scenario (SCN-1) and the reprocessing strategies. The storage costs are reduced three times for SCN-2 and 3.6 times for transmutation scenarios (SCN-3 and SCN-4) while the gallery length for FD is reduced to 42% and 29% respectively. These costs are a part of the DDD costs and represent ~3.5% of the LCOE for SCN-1, ~1% for SCN-2 and ~0.7% for SCN-3 and SCN-4.

On the other hand, there are two additional contributions not included in Fig. 10: RepU storage and final disposal of Long-Lived Intermediate Level Wastes resulting from fuel reprocessing. They will be addressed in a future study.

In order to analyze the influence of each technology to the scenario, the generation cost per reactor type was additionally calculated. The result is depicted in Fig. 11, where all scenarios are plotted together. It can be clearly seen that the energy cost per reactor type increases with the reactor technology complexity. Here, it has been assumed that each technology unit must pay back the investment during its lifetime, presented in Table 1.

Differences between scenarios for LWR_UOX and LWR_MOX technologies (GEN II) are explained solely by the DDD costs. Note that none of these technologies include the investment cost; obviously, this could increase the generation costs, reducing the differences between GENII and GENIII technologies.

Table 5
Summarized economic results per scenario.

	SCN-1	SCN-2	SCN-3	SCN-4
LCOE (cent€/kWhe)	4.65	5.58	6.20	6.09
Investment cost (%)	61.3	68.8	60.4	68.1
Fuel cost (%)	10.9	6.4	18.0	8.8
O&M (%)	22.2	21.6	19.0	20.3
DDD cost (%)	5.6	3.2	2.6	2.8

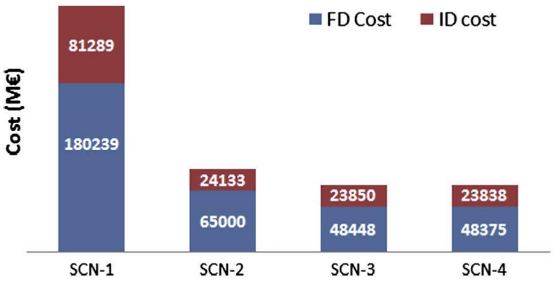

Fig. 10. HLW storage costs per scenario for interim and final disposal.

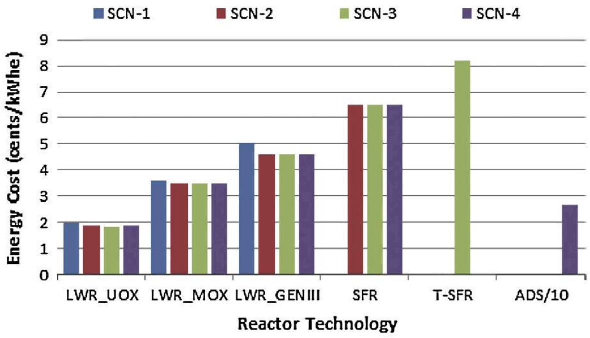

Fig. 11. Energy cost by technology for the different scenarios. Note that: (i) ADS cost is divided by 10, and (ii) as explained in the text, LWR_UOX and LWR_MOX are considered legacy technologies with capital expenses not included.

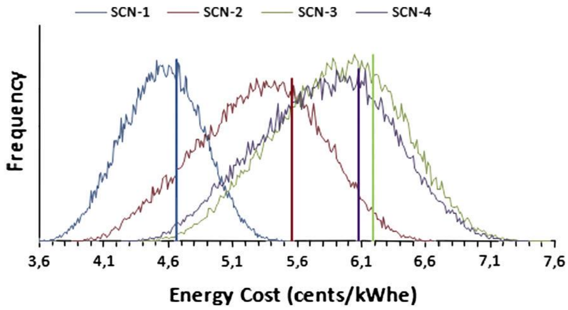

Fig. 12. Histograms of LCOE statistical analysis and the Best Case results.

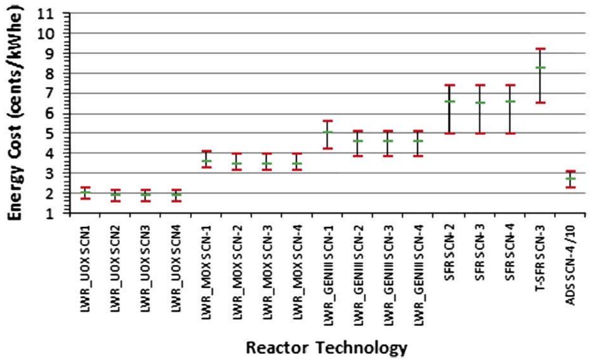

Fig. 13. LCOE range and the Best Case.

For LWR_GENIII, differences between scenarios are due to investment costs, mainly in SCN-1, because there is a fraction of LWR_GENIII in SCN-1 commissioned but with a lifetime beyond the end of the scenario (so a fraction of its generated energy is not accounted for). SFR group remains almost unchanged because its cost is very similar between scenarios. Moreover, for T-SFR, the difference regarding SFR is caused by the expensive cost of its fuel type. It is notorious the large cost obtained for the ADS in scenario SCN-4 (divided by 10 in the figure), more than 3 times more expensive than T-SFR in SCN-3. However, the impact of this technology to the LCOE of SCN-4 is very similar to T-SFR in SCN-3 due to the small contribution to the energy production of this specific technology (~3% averaged).

6.2.2. Uncertainty analysis

Uncertainties in the LCOE have been estimated via a Monte Carlo 'brute force' methodology using 50,000 different histories. In this work, triangular distributions have been used for each unit cost. These distributions are commonly utilized when there is limited information but lower limit, upper limit and best-estimate values are available for the unit costs.

In this analysis the lower and upper limits have been taken from NEA 2006 (NEA/OECD, 2006) resized to the values appearing in the ARCAS project (Klaasen et al., 2012), which have been taken as the modes of the triangular distributions. These values are shown in Table 2 above.

Fig. 12 shows the result of the statistical analysis of the cost assessment. It has to be noted that the Best Case values do not match the average values of the uncertainty distributions. This is a consequence of the distributions taken from the bibliography for the unit costs, where the Best Case value (mode of the distribution) does not usually match the median.

It can be observed that, although the Best Case of the LCOE of scenario SCN-2 was around 37% larger than the value for SCN-1, there is a significant overlapping between the two distributions. This means that the probability that SCN-2 is more expensive than SCN-1 is significant, but giving an exact value for the relative increment in the energy cost for these scenarios may be senseless. A similar rationale can be made for the scenarios with dedicated transmutation. Although the LCOE of these scenarios is around 10% larger than the LCOE of scenario SCN-2, the overlapping between the distributions is even more significant. This figure also shows that there are no meaningful differences between the two transmutation strategies SCN-3 and SCN-4.

The influence of each technology to the generation cost by reactor type is shown in Fig. 13, where the green lines represent the Best Case values of the LCOE and the red lines show a 2σ interval (95% of the values) around the mean of the statistical analysis of the cost assessment. As mentioned above, the energy cost by reactor type clearly increases with the reactor technology complexity, although it can be seen that some distributions slightly overlap. Note that the ADS cost is again displayed after divided by 10, and that investment costs have not been included for LWR-GENII technologies.

The contribution to the uncertainties by cost type can be seen in Fig. 14. The investment cost is the most important source to the uncertainties shown in Fig. 12, with over 80% for all scenarios. The second source come from the O&M cost followed by those

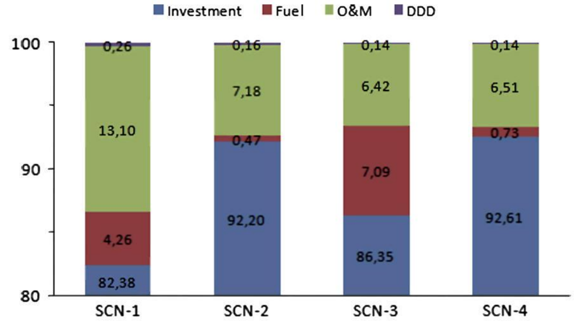

Fig. 14. Contribution to the uncertainties by cost type. Note that the vertical axis shows the uncertainty ranging from 80% to 100%.

one caused by the fuel cost. Note that this fuel cost, the uncertainties are significant smaller in SCN-2 and SCN-4. This is caused by its lower contribution to the energy cost (6.4% and 8.8% respectively) and the lower range of cost for fabrication and reprocessing cost for FR fuel (without MA), which is uppermost in both scenarios. For every scenario, the DDD cost represents the smallest contribution to the uncertainty.

7. Conclusions

In this work four fuel cycle scenarios involving transmutation options have been simulated by means of TR_EVOL code in order to analyze – in economic and resources terms – the impact of the implementation of advanced technologies and concepts including GEN-III+ and GEN-IV reactors and advanced partitioning and transmutation techniques.

The feasibility of all these fuel cycle scenarios is confirmed in terms of resources availability. We have checked that there is no constraint in terms of natural uranium, depleted uranium, and Pu and MA availability.

Concerning the transmutation performance, we have found that, without a transmutation strategy for MA, fast reactors reduce significantly the amount of Pu in the final repository (to a 1% of the total). Additionally, a MA transmutation strategy is needed to reduce the amount of MA in the final disposal. This objective can be achieved (to less than 1% of the total MA amount) with a strategy including SFR for both electricity generation and MA transmutation, and also in a strategy where SFR is responsible for energy generation and ADS is essentially dedicated to MA burning.

Regarding the economic analysis, the estimations show an increase of LCOE – averaged over the whole period – with respect to the reference scenario of 20% for SFR strategy (SCN-2) and $\sim$35% for transmutation scenarios. This result is fully valid in spite of some special hypotheses included in this work, common to all scenarios, such as the consideration that the current fleet of LWR had been paid off at the beginning of the scenario. We have also found that the main contributor to the cost of electricity is the investment cost, responsible of 60–69% of the total.

Results show that the cost of the HLW disposal can be reduced for approximately a factor 4 in a strategy using fast reactors and 5 times with transmutation strategies. This cost represents a small relative value to LCOE compared to other contributions (it is 3.7% for SCN-1 and less than 1% for advanced cycles).

It has also been found that investment costs are the most important parameters that have to be carefully considered to assure a proper estimation of the energy cost in the standpoint of uncertainties reduction. Also, results show that a vigorous policy of capital costs reduction for future technologies deserves much attention.

Investment outcomes are significantly dependent on the input data and the range of the uncertainties. Unfortunately, published unit cost uncertainties are too large to find optimal answers to any parameter by means of an economic criterion.

Concerning the TR_EVOL computational tool, it has been proved to be powerful enough to simulate different types of fuel cycle scenario including economic implications.

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